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Quantifying seedbed condition using soil physical properties

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Abstract

Soil physical condition following tillage influences crop yield, but the desired condition cannot be adequately evaluated with current techniques. This study was conducted to determine a soil condition index (SCI) that could be used to select the type of implement needed to achieve an optimal seedbed with minimum energy input. Effects of bulk density, moisture content, and penetration resistance resulting from three tillage systems (no-till, chisel plow and moldboard plow), on the growth of corn (*Zea mays* L.) were studied. The experiment was conducted in Boone County, Ames, IA, on soils that are mostly Aquic Hapludolls, Typic Haplaquolls and Typic Hapludolls with slopes ranging from 0 to 5%. The results are from the 2000 season, which had normal weather conditions and yield levels for the Iowa state. The average corn grain yield at this site was 9.36 Mg/ha. At the V2 corn growth stage, the average dry biomass was 1.34 g per plant. The soil physical properties were normalized with respect to reference values and combined via multiple regression analysis against corn biomass at V2 stage into the SCI. Mean SCI values for the no-till, chisel and moldboard plow treatments were 0.86, 0.76, and 0.73, respectively, all with a standard error of 0.0127. The lower the SCI, the more optimum the soil physical conditions. An analysis of variance showed significant differences among mean SCI for each treatment (p-value $= 0.001$). The use of the SCI could improve the tillage decision-making process in environments similar the one studied.

Keywords: Bulk density; Penetration resistance; Moisture content; Soil quality; Tilth; Soil condition

1. Introduction

Tillage has many purposes including the creation of a suitable seedbed for germination and plant growth, incorporation of agricultural chemicals and crop residues, burying weeds, or construction of certain land structures for erosion control. For seedbeds, tillage often pulverizes the soil allowing for unimpeded root growth and easy flow of air and water. Many of the benefits of tillage are well known, but the amount necessary to achieve optimum soil conditions is not.

The tilth or soil condition resulting from the use of different tillage tools depends on both the type of implement used and the soil condition when tillage occurs. At present, it is not possible to consistently predict the resulting soil conditions from any tillage operation. According to Dexter (1988), too much emphasis has been placed on primary failure of soil surfaces and not enough on the crumbling produced by tillage. Although, some tillage is generally needed, excessive tillage can cause the soil to be vulnerable to wind and water erosion. It can also increase the operational costs incurred by farmers.

Previous attempts to quantify the seedbed conditions following tillage have been made, but it has been difficult to determine which soil physical properties

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should be used to measure tilth. Researchers often use porosity, bulk density, structure, compaction, particle size distribution, and clod size distribution (Luttrell, 1963; Fragin, 1986; Hakansson, 1990; Steyn and Tolmay, 1995; ESCAP, 1995). Among these properties, bulk density remains the most popular and widely measured. Bulk density changes are most evident following tillage when compared to other physical soil condition indicators. Burov et al. (1973), however, warned that the field method for determining bulk density is insufficiently accurate and gives only an approximate idea of soil make up. Karlen et al. (1999) further state that since several factors (such as moisture and organic matter content) can confound bulk density measurements, it should not be the only soil physical factor used as a soil quality indicator.

Recently, some soil properties have been mathematically adapted to both describe the tilth and the capacity of a soil to support a particular crop for maximum yield. Measurements such as the K coefficient (Fragin, 1986), roughness index (Gupta et al., 1991), resistance to penetration (Becher et al., 1997), relative compaction (Carter, 1990) and degree of compactness (Hakansson, 1990; da Silva et al., 1997; Hakansson and Lipiec, 2000) were proposed by the researchers as possible ways to quantify soil condition.

The degree of compactness, relative compaction and resistance to penetration indices, use a single soil property to model a complex environment. Therefore, they risk oversimplifying the tilth status and also may result in a mathematically correct relationship that has no physical or biological relationship to crop growth and development.

Combining several soil physical factors to account for the complexity of the soil environment was a common goal among researchers in the 1990s (Singh and Colvin, 1992; Williams et al., 1992; da Silva et al., 1994, 1997; da Silva and Kay, 1997). Regression procedures were used by Williams et al. (1992) to model tilth. They selected only those soil variables that made a significant contribution toward yield. da Silva et al. (1994) characterized the structural quality of the soil using the least limiting water range index (LLWR). The LLWR was a range in soil water content after rapid drainage had ceased and where water potential, aeration, and mechanical resistance to root penetration had minimal effect on plant growth (da Silva and Kay, 1997). They found that using the degree of compaction (relative density) instead of bulk density improved the applicability of the model by diminishing differences in values of LLWR between different soil types. Similar results were obtained by da Silva et al. (1997). However, calculation of LLWR is time consuming, therefore limiting its adoption for use on a routine basis (da Silva and Kay, 1997). Thus, pedo-transfer functions to model the influence of tillage and soil properties on LLWR have been developed in order to reduce the amount of required data collection. Singh and Colvin (1992), and Singh et al. (1992) used tilth coefficients to model the relationship between soil variables and yield.

The "tilth index" was a quantitative value used to describe soil conditions relating to plant growth ranging from 0.0 for worst to 1.0 for best conditions. Tapela and Colvin (1998) found that determining the tilth coefficients was iterative and arbitrary. They modified Singh et al. (1992)'s linear correlation model to a new quadratic relationship. However, neither model could consistently distinguish which tillage method produced better tilth. This confirmed that, their methods need further refinement and investigation.

Soil condition can be examined holistically by considering the chemical, biological, and physical factors affected by tillage. This approach is consistent with the concept of soil quality that has been extensively researched by Karlen et al. (1999). Simply defined, soil quality is the capacity of the soil to function. Each soil indicator supporting a given function is related quantitatively to the function it supports (Harris et al., 1996). Using scoring functions requires no simulation modeling to estimate the functional relationships between soil properties and soil quality, and the method is easy to use.

Despite the attempts made over the years, seedbed evaluation remains subjective. Being able to quantify such a condition would allow farmers to target the intensity of their tillage operation. This would eliminate unnecessary costs incurred by farmers using aggressive tools to achieve what could be done using lower disturbance tools. It would also help to interpret data from various soil measurements and show whether management is having the desired results on productivity (Granatistein and Bezdicek, 1992). Research is, therefore, needed to identify appropriate parameters and protocols for combining various soil measurements into meaningful index values at various scales.

The objective for this research is to identify soil physical properties through regression methods, and use them to make pair-wise comparisons of seedbed conditions resulting from three different tillage practices (no-till, reduced tillage and conventional tillage).

2. Materials and methods

A field experiment was conducted at the Kelly experimental farm operated by Iowa State University in Boone County, Ames, IA. The experiment was a randomized complete block design comparing no-till, fall moldboard and fall chisel plowing. No further cultivation was done following primary tillage. Roundup®[1] (Glyphosate) herbicide was applied in spring 1 week before planting to control weeds. The test crop was corn (*Zea mays* L.), pioneer variety 34B23 and planted at a seeding rate of 74 500 plants per hectare. Liquid urea–ammonium nitrate fertilizer (32% N) was applied at a rate of 0.21 t/ha on all plots. Previously the site had been managed using a soybean (*Glycine max*. L), corn (*Z. mays* L.) and oats (*Avena sativa*) rotation for 3 years. The primary tillage tool used in previous seasons was fall moldboard followed by spring cultivation. The soils at the experimental site are Aquic Hapludolls, Typic Haplaquolls and Typic Hapludolls with slopes ranging from 0 to 5% (USDA, 1981). The average monthly temperature during the growing season (5 May–13 October) was 16 °C and with average mean monthly precipitation of 60 mm.

The experiment was set-up by establishing 12 plots (7.6 m wide and 53.3 m long) that lay side-by-side length wise. Four blocks of three plots each were created across the direction of the field slope. Measurements were made on each plot in the inter-row spaces not affected by wheel traffic in order to identify differences in bulk density (D_b), penetration resistance or cone index (CI), and moisture content (MC) due to tillage. The inter-row spacing was 0.76 m, making a total of 10 rows per plot.

Before tillage in fall 1999, D_b was measured within the surface layer using undisturbed cores that were 76 mm diameter by 51 mm high. The sampling depth was from the soil surface. Each plot was sampled six times in a staggered design spanning the length of the field, thus providing a total of 72 D_b measurements. The same cores collected for D_b were also used to determine the soil moisture content by the oven drying method (Blake and Hartge, 1986). For measurement of penetration resistance, a standard digital cone penetrometer (13 mm^2, 12 mm diameter and 30° cone slope) was used. CI measurements were also taken six times in each plot from locations beside D_b measurements. Readings were taken at 5, 10, and 15 cm depths (plowing zone) at each location following the procedure described in the ASAE standard S313.2 (ASAE, 1993). A second sampling for D_b, CI, and MC was made in spring 2000 before planting.

From the D_b measurements, proctor density ratio (PDR) was computed as D_b/D_{bp}. The value of D_{bp} in the ratio is the proctor density of the soil at the same moisture content when D_b was measured. It was important to have the ratio at the same moisture content so that comparison can be made across similar soils at different moisture levels. PDR ranges between 0 and 1 for cultivated fields. A low PDR value will indicate a loose soil while a dense soil will approach 1.

Penetration ratio (PR) was calculated from penetration resistance values. It was computed as $(\mathrm{MCI} - \mathrm{CI})/\mathrm{MCI}$. The value of CI is the average penetration resistance measured at the three depths for each point location, and MCI (3.5 MPa) is the maximum cone index found in most fields (Tapela and Colvin, 1998; Vepraskas and Wagger, 1989). The 3.5 MPa was used as the limiting value instead of the common crop growth limit of 2 MPa (da Silva et al., 1994; Singh et al., 1992) so that the CI can be related to the maximum compaction in the field. The value is an approximation as it is strongly dependent on moisture content, a factor accounted for in the moisture ratio (MR).

MR was derived from the measured moisture content values and is computed as $1 - \left[\left(\sum(\mathrm{MC}-\mathrm{FC})^2\right)/6\right]^{1/2}/\mathrm{FC}$. It describes the variation of the field moisture content from field capacity (FC) based on an

[1] Trade names are provided for the benefit of the reader and do not imply endorsement or preferential treatment of the products by Iowa State University or the USDA/ARS National Soil Tilth Laboratory.

average of six moisture samples collected per plot. FC was assumed to be the moisture of a soil held between 0.01 and 0.03 MPa matric suction (Klenin et al., 1970; da Silva et al., 1994). The pressure cell procedure for determining soil moisture at FC is outlined in Klute (1986). For this study, five undisturbed core surface soil samples ($76\,\mathrm{mm}$ diameter $\times$ $76\,\mathrm{mm}$ height) were collected prior to tillage in fall 1999 and were used for the low range pressure systems (0.03 MPa). Moisture levels were measured after subjecting the samples to 0.03 MPa suction for 72 h. The average moisture content at 0.03 MPa was assumed to be equivalent to the FC.

Soil sampling for the Proctor compaction test was done by randomly collecting four samples of approximately 20 kg each from throughout the whole field in fall 1999 and allowing the samples to air-dry. After drying, clods were broken down using a soil grinder and each sample was sieved through a 4.75 mm sieve to obtain about 12 kg of soil. The sieved samples were mixed together and again divided into five sub-samples of about 2.3 kg each. The sub-samples were then wetted to varying moisture contents by adding increasing amounts of water and thoroughly mixing in sealed plastic bags. The sub-samples were allowed to remain in the bags for 5 days at room conditions (22 °C). Each day they were stirred to obtain a thorough mix and uniform moisture distribution. After that the standard proctor density test was performed as outlined in ASTM D 698 standard (ASTM, 1998; Liu and Evett, 2000). The D_{bp} was plotted against soil moisture and the maximum D_{bp} was determined graphically.

With values for PDR, PR and MR, the soil condition index (SCI) for each plot following tillage was calculated as $(p_1 \times \mathrm{PDR} + p_2 \times \mathrm{PR} + p_3 \times \mathrm{MR})$. The p_i-values $(i = 1, 2, 3)$ were the regression coefficient proportions for PDR, PR and MR, respectively, in the multiple linear regression model where all the three parameters were included to predict yield. Crop growth measurements were average biomass per plant at V2 growth stage (Ritchie et al., 1993) and grain yield. Six locations were randomly identified within each plot for plant biomass sampling. Sampling was done by uprooting single plants on three rows for each location, and determining the average dry mass of the above-ground material. An assumption was made that proctor values at the same moisture content and water retention at similar tensions were uniform across the whole field.

The Statistical Analysis System (SAS®, 1990) package was used to randomly assign treatments to the plots on the different blocks. An analysis of variance (anova) was performed to assess the influence of tillage method on yield and plant dry biomass at the V2 corn growth stage. Multiple regression analysis was also done to determine the influence of PDR, PR and MR on yield and plant dry biomass at the V2 corn growth stage. The anova and multiple regression used mean values for the six PDR, PR and MR measurements from each treatment. Mallows' C_p model selection procedure (SAS, 1990; Ramsey and Schafer, 1997) was used to determine the best regression model (among all possible independent variable combinations) that could be used to predict yield and plant dry biomass at V2 growth stage. An analysis of variance was also done to determine if there was any difference in mean SCI for each tillage treatment within the blocks.

3. Results and discussion

Measured values of D_{b}, MC and CI ranged from 1.16 to $1.69\,\mathrm{Mg\,m^{-3}}$, 16–30% and 0.6–3.8 MPa, respectively, across the whole field before tillage in fall 1999. At planting in spring 2000, the values ranged from 0.94 to 1.66 $\mathrm{Mg\,m^{-3}}$, 9–27% and 0.1–3.2 MPa for D_{b}, MC and CI, respectively. The lower D_{b} and CI values in spring sampling are a result of tillage operations that loosened the soil after fall sampling. Moisture content was also lower in spring because sampling was done following period of no rain. However, all the three parameters were within levels that would not impede plant growth. Table 1 shows average values for PDR, MR, PR and response values from each plot based on spring sampling data. Analysis of variance on mean tillage biomass within each block was significant (p-value $= 0.02$) but was not significant for mean tillage yield within blocks (p-value $= 0.16$). Mean biomass for moldboard tillage was significantly different from either chisel or no-till systems when tested with Tukey multiple comparison test. The non-significant yield differences may be due to compensatory growth after V2 stage as found on soybeans by Yusuf et al. (1999).

Multiple regression of PDR, MR and PR against biomass at V2 stage based on fall sampling data had a

Table 1
Summary results for spring 2000 data analyzed from Kelly fields

Block	Tillage	PDR[a]	MR[b]	PR[c]	Biomass (g per plant)	Yield (Mg/ha)
1	N[d]	0.89	0.78	0.37	0.98	10.06
1	C[e]	0.76	0.92	0.66	1.16	10.40
1	M[f]	0.70	0.79	0.85	1.22	9.58
2	M	0.70	0.84	0.88	1.24	9.80
2	C	0.71	0.81	0.66	1.33	10.00
2	N	0.93	0.76	0.41	1.01	8.13
3	M	0.74	0.76	0.90	1.25	9.19
3	N	0.94	0.64	0.62	1.27	9.05
3	C	0.85	0.60	0.67	1.69	9.43
4	M	0.80	0.56	0.83	1.83	8.77
4	C	0.81	0.53	0.67	1.74	9.11
4	N	0.89	0.65	0.36	1.38	8.81

[a] Proctor density ratio.
[b] Moisture ratio.
[c] Penetration ratio.
[d] No-till.
[e] Reduced till.
[f] Conventional till.

coefficient of determination of 0.71. However, the only significant regression coefficient was that for MR ($p = 0.05$). Letey (1985) also noted similar result that water was a dominant controlling factor related to plant growth and soil penetration resistance tends to increase with increasing moisture tension (Bilanski and Varma, 1976), affecting subsequent crop growth. Including blocking factor in the same regression model did not provide much improvement ($R^2 = 0.72$). Similar results were obtained when the same data was used in a regression model of PDR, MR and PR against yield values. The model had a coefficient of determination of 0.47 and again only MR had a significant coefficient ($p = 0.03$).

The results based on spring data show that a decrease in MR leads to an increase in PDR and a corresponding decrease in PR (Fig. 1). Essentially, it means low moisture content is associated with an increase with both bulk density and penetration resistance resulting in a decrease in both plant and root growth (Letey, 1985). The association occurs because greater reduction in water content lead to a greater increase in soil cohesion and internal friction leading to higher bulk density and penetration resistance (Bilanski and Varma, 1976). Multiple regression of PDR, MR and PR on biomass based on spring sampling data had a coefficient of determination of 0.85 (p-value $= 0.001$). The coefficient for PR was not significant ($p = 0.92$). The reason may be that PR is closely related to PDR ($r = -0.76$), which was already included in the model. Other correlations between soil variables were not as high as between PDR and PR (PDR versus MR $= -0.43$; PR versus MR $= 0.05$).

The multiple regression coefficient of determination of yield against PDR, MR and PR was 0.49

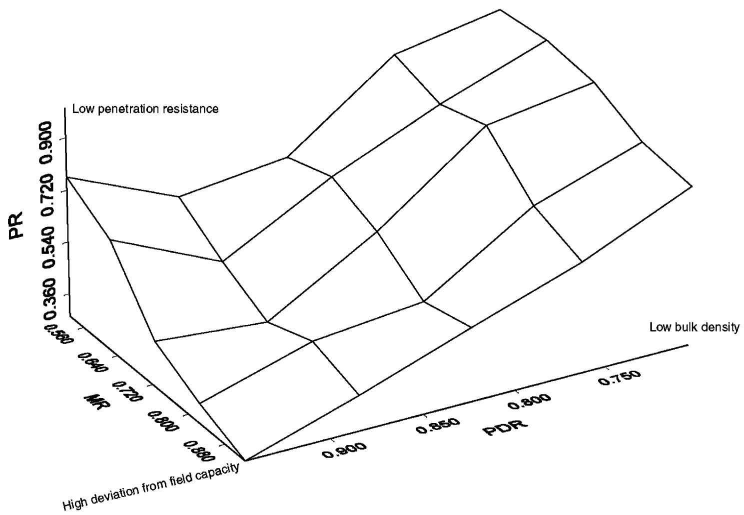

Fig. 1. Relationship between soil physical properties for spring 2000 data.

Table 2
Parameter estimates for the biomass regression model

Variable	DF	Parameter	Standard error	t-Value	p-Value
Intercept	1	4.39	1.02	4.31	0.0026
PDR	1	−1.69	0.79	−2.13	0.0663
MR	1	−2.03	0.38	−6.09	0.003
PR	1	−0.03	0.34	−0.10	0.9211

(p-value $= 0.127$). It showed there was no significant difference in yield due to the independent variables. Unlike biomass, yield was measured at the end of the season after other environmental factors such as precipitation and temperature had affected the crop. Thus, it is not possible to isolate differences due to these factors from the ones being tested. The lack of linear correlation between yield and biomass at V2 stage is confirmed by a low correlation coefficient of -0.23. Because of low correlation with yield, no further interpretation was done on the yield model. A regression equation (Eq. (1)) for biomass against the independent variables was written using the estimated regression parameters (Table 2) as

$$\text{Biomass} = 4.389 - 1.69\text{PDR} - 2.03\text{MR} - 0.03\text{PR} \tag{1}$$

A t-test to determine if any of the parameter estimates was equal to zero showed that the parameter for PR was not significant (Table 2). Therefore, it was safe to exclude PR from the full model as it contributed very little to individual plant biomass level. The t-test was confirmed when the Mallows' C_p model selection criterion was used (Table 3). Accordingly, the model with only PDR and MR as independent variables is selected ($C_p = 2.01$).

Table 3
Models ranked according to C_p selection method

Rank	C_p-value	Variables in model
1	2.01	PDR, MR
2	4.00	PDR, MR, PR
3	6.52	MR, PR
4	12.67	MR
5	39.03	PDR, PR
6	40.58	PR
7	46.39	PDR

The exclusion of the PR from the model does not mean that penetration resistance was not important in soil physical conditions. The reason may be that it was so closely related to the PDR ($r = -0.76$) that it was in fact a linear transformation of this variable. Alternatively, it may be that the form in which PR was presented in the model needs some modification such as log transformation so that it relates better to individual plant biomass.

After performing the regression procedure using PDR, PR and MR, the proportion of improvement to the coefficient of determination as each factor was added to the model was used to define the SCI shown in Eq. (2). Since the contribution due to PR was negligible, only two variables remained in the model.

$$\text{SCI} = 0.73\text{PDR} + 0.27\text{MR} \tag{2}$$

Coefficients in Eq. (2) are the proportions of variation in Eq. (1) explained by each of PDR and MR. Eq. (2) is specific for the soil environmental conditions during the studied season at the Kelly field. However, it can be easily adapted to fields of similar soil types by determining the FC and the proctor density levels for those soils and substituting the values in the regression model.

From the way the SCI is designed, it will range from zero to unity. A low value will reflect desirable conditions and a value of 1 will mean the worst conditions. For example, if a farmer goes to the field and takes some soil measurements in spring before tillage and calculates the SCI to be 0.9, he or she will know the conditions are not suitable for corn early growth and that some tillage will be necessary unless done for other purposes such as fertilizer incorporation and weed eradication. Analysis of variance showed a significant difference between SCI for each treatment within each block (p-value $= 0.001$). Mean SCI values for no-till, chisel and moldboard plow were 0.858, 0.763, and 0.735, respectively, with a standard error of 0.0127. No-till SCI value was significantly different from both moldboard SCI (p-value $= 0.001$) and chisel SCI (p-value $= 0.001$). That means SCI can be used to distinguish the soil physical conditions created by the different tillage methods. The critical SCI level has not yet been determined, but will depend on what the farmer assumes as a reasonable individual plant biomass level to assure a good yield. When blocking was included in the regression models, it had a significant effect on biomass (p-value $= 0.027$). This suggests that there may be other confounding factors (biological, climatological or chemical) that are difficult to represent because the research modeled only the physical properties of the soil. Confounding factors include organic matter content, soil temperature and soil aeration. Tilled soil is warmer than untilled soil during warming periods and the reverse is observed during cooling (Hadas, 1997). Similarly, oxygen distribution in the soil depends on the continuous air-filled pores that are characteristic in tilled soil. These factors need further investigation.

4. Final comments

Regression procedures were used to develop an SCI that related soil physical properties to different tillage systems. The results are preliminary since they represent data from a single season at one location and crop. A fully developed SCI would represent a quantitative method that can be used by farmers and researchers to evaluate soil following tillage, and make management decisions regarding tillage intensity required. Such evaluations would eliminate the unnecessary costs incurred by farmers using aggressive tools to achieve what low disturbance tools can do. Further, research is required to validate the model. Long-term field results are also necessary to make sure the model does not capture only one-time response of the crop to a given set of soil conditions.

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